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Enhancement flame flashback resistance against CIVB and BLF in swirl burners

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Abstract

Swirl combustors have proven as effective flame stabilisers over a wide range of operation conditions thanks to the formation of well-known swirl coherent structures. However, employment of swirl combustors to work on lean premixed combustion modes while introducing alternative fuels such as high hydrogen blends result in many combustion instabilities. Under these conditions, flame flashback has been considered as one of the major instability problems that have the potential of causing considerable damages of the combustion systems hardware in addition to the significant increase in pollutant levels. Combustion Induced Vortex Breakdown (CIVB) is considered a very particular mode of flashback mechanism in swirling flows as this type of flashback occurs even when the fresh mixture's velocity is higher than the flame speed, consequence of the interaction between swirl structures and swirl burner geometries. Improvements of burner geometries and manipulation of swirl flows can produce good resistance against this type of flashback. However, increase flame flashback resistance against CIVB can lead to an increase in the propensity of another flashback mechanism, Boundary Layer Flashback (BLF). Thus this paper presents an experimental and numerical approach that allows the increase in CIVB resistance by using diffusive air injection and simultaneously avoid BLF by changing the wall boundary layer characteristics using microsurface grids as a liner for the nozzle wall. Results show that using those two techniques together has promising potentials regarding wider stable operation for swirl combustors, enabling them to burn a great variety of fuel blends safely.

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Keywords: CIVB; BLFB; Velocity gradient

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Nomenclature

BLF	Boundary Layer Flashback	R_0	Nozzle radius [mm]
CIVB	Combustion Induced Vortex Breakdown	U	Axial velocity [m/s]
CRZ	Central recirculation zone	Y	LDA measurement level downstream nozzle [mm]
CFD	Computational fluid dynamics	Φ_{stable}	Equivalence ratio of stable operation
D	Nozzle exit diameter [mm]	Φ_{FB}	Equivalence ratio close to flashback

1. Introduction

In most practical combustion systems the achievement of high flame flashback resistance depends on flame stabilisation downstream the burner nozzle, which rests on the equilibrium between flame speed and incoming flow velocity at the reaction zone both in magnitude and direction. This balance, in turn, is a function of different parameters such as burner configuration or geometry, the degree of mixing (premixed, partial premixed or diffusive), fuel type, initial conditions of the mixture (pressure and temperature) and working conditions inside the combustion chamber.

However, avoiding flame flashback by controlling the equilibrium between incoming flow velocity and flame speed is not always achievable, as flashback due to inherent swirling structures can occur even when the incombustible mixture velocity is higher than the flame speed. Thus, flashback mecanisms can lead to dramatic consequences when high turbulent flame speed fuels such as those based on highly hydrogenated blends are used [1-4]. One of these mechanisms, Combustion Induced Vortex Breakdown (CIVB), is considered a fast acting flashback mechanism that appears in swirl burners as a consequence of the formation of the Central Recirculation Zone (CRZ) [5] and that can propitiate the movement of the flame inside of feeding passages.

Swirling flows are characterised as highly complex phenomena because their inherent three-dimensional time-dependent structures. Therefore, flow field manipulation, particularly at the region where the upstream flow field is distorted by the burner geometry, is of high importance in controlling flame stability downstream the burner nozzle. Many studies have investigated flame flashback mechanisms in swirl combustors, and they suggested many techniques for mitigating flame flashback either by doing some geometrical enhancements or by promoting flow field patterns. Flame flashback due to CIVB received particular attention amongst other flashback mechanisms since it is one of the prevailing flashback mechanisms in swirl combustors and represents an obstacle in developing combustion systems, especially those fed by high flame speed fuels such as high hydrogen blends [6, 7].

Central fuel injectors or bluff bodies proved their potential ability in anchoring the CRZ downstream the burner nozzle with a considerable flame flashback resistance, especially against CIVB. However, despite the vigour of this flame stabilisation technique, central fuel injection cannot totally mitigate flame flashback. This method of flow field manipulation is based on injecting either fuel or air diffusively through the centre of the flow field in order to change the defect of negative axial velocity and turbulence characteristics of the CRZ. However, although axial injection can compensate the defect of the axial velocity at the burner centre-line, it could enforce the flame to propagate via another flashback mechanism, wall Boundary Layer Flashback (BLF).

Flame flashback via wall boundary layer depends on many parameters such as the flow field characteristics, equivalence ratio, pressure, temperature, wall temperature, confinement type, the state of the boundary layer and the geometry of interior liners in the burner nozzle [8]. The geometry of the nozzle wall plays an important role in upstream flame propagation during boundary layer flashback, i.e., the interaction between nozzle wall and flame can affect directly the amount of heat flux which consequently changes the wall quenching distance [9]. The interaction between nozzle wall surface and the parallel flow generates a viscous drag which produces an adverse pressure gradient, consequently promoting velocity gradient. Microsurfaces of different geometries can positively increase the boundary layer flashback resistance. Those surfaces have high potentials in reducing drag effect in the wall adjacent region.

Thus this study presents an experimental and numerical approach about the validity of using diffusive air injection and the enhancement of the wall boundary layer characteristics via microsurfaces to achieve good flame flashback resistance for both CIVB and BLF.

2. Experimental setup and numerical approach

The 150 kW tangential swirl burner used in this work is illustrated in Figure 1. The burner has two tangential inlets of 67 mm ID; the burner exit is 76 mm ID. The diameter of the tangential inlets can vary using different inserts, while the exit diameter can change using different nozzle configurations. Thus it is possible to have variable geometric swirl number from 0.913 up to 3.65. However, in this work, only a 0.913 swirl number has been used. The original base plate containing the fuel diffusive injector (Central injector) was replaced by a modified design that allowed axial air injection in addition to fuel. A 150 µm micromesh grid has been used as a liner to investigate the change of nozzle surface and its impacts on the boundary layer. Figure 2 shows the position of the micromesh inside the burner nozzle. This microsurface was numerically simulated and assessed somewhere else [10]. The instantaneous velocity components downstream the burner mouth have been measured by Laser Doppler Anemometry (LDA). The LDA system used was a one component Flowlight LDA (Dantec) operated at backscatter mode. The light source consists of an argon ion laser, and the focal length of the lens was 500 mm. Aluminium oxide AL_3O_2 seeding was used in the experiments with a particle size of approximately less than 10µm.

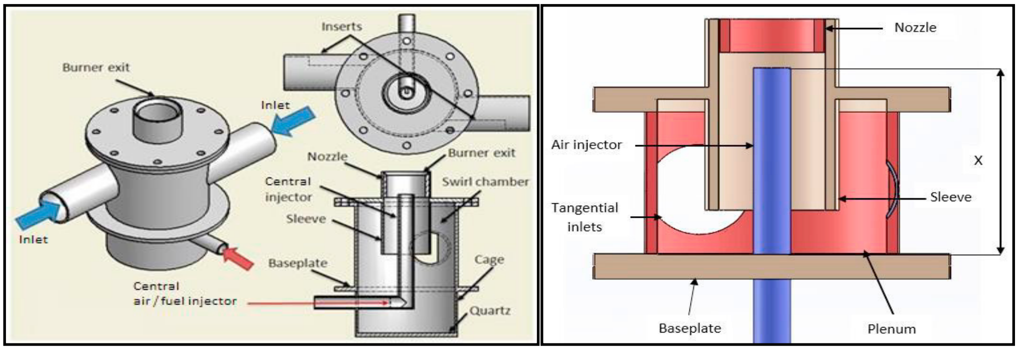

Fig. 1. 150 kW tangential swirl burner.

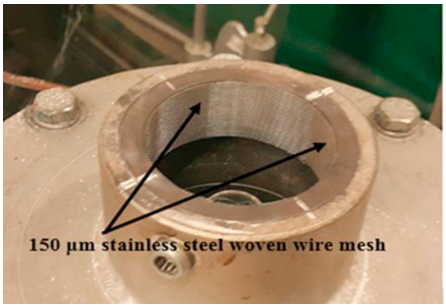

Fig. 2. Position of the microstructures inside the burner nozzle.

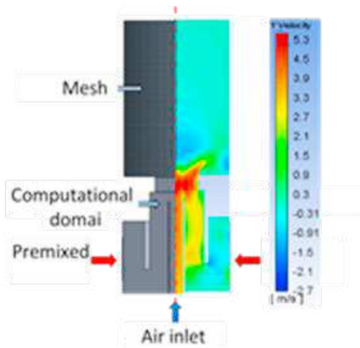

Fig. 3. Schematic view of the computational domain, Physical model, mesh, and axial velocity contour.

ANSYS FLUENT 17.2 has been used to simulate the cold swirl flow in the 150 kW tangential swirl burner. The k-ε turbulent model was used in the simulation. A very fine structured mesh was designed and employed for the tests. The total number of nodes of the grid is 11,117,541 with 10,985,610 elements and minimum skewness of 0.33. Figure 3 illustrates the computational domain, physical model, generated mesh, and axial velocity contour for the tangential swirl burner.

3. Result and discussion

3.1. *Diffusive air injection for CIVB resistance*

The modified burner baseplate allows the movement of a central air injector at different positions with respect to the base plate. However, in this study, just one position (X =150 mm) was used to investigate the effect of air injection downstream the burner mouth on the axial velocity at different tangential flow rates. The amount of central air injection is crucial in obtaining flame stabilisation, from one hand it should be robust and coherent enough to prevent upstream flame propagation, and on the other hand, the ratio of axial to tangential injection must be kept as low as possible to avoid swirl strength deterioration. Based on preliminary tests it was found that the optimum amount of central air injection to achieve coherent air jet and avoid swirl strength degradation is (50 l/min), this ratio represents 3-10 % of the total mass flow rate at different inlet tangential flow rates. Figure 4 shows the effect of diffusive air injection on the CRZ position and the velocity downstream the burner mouth. Axial air injection considerably reduces the negative flow velocity values of the central recirculation zone and pushes the CRZ downstream in such way that the vortex bubble is still slightly away from the nozzle exit plane. Keeping the CRZ tip at a certain distance from the nozzle exit plane allows increasing volume expansion under the effect of the heat generated from the flame, consequently preventing the formation of a recirculation bubble at the tip of the CRZ, which can lead to the onset of the CIVB [11]. These results are based on one-dimensional LDA measurements of axial velocity downstream the burner mouth.

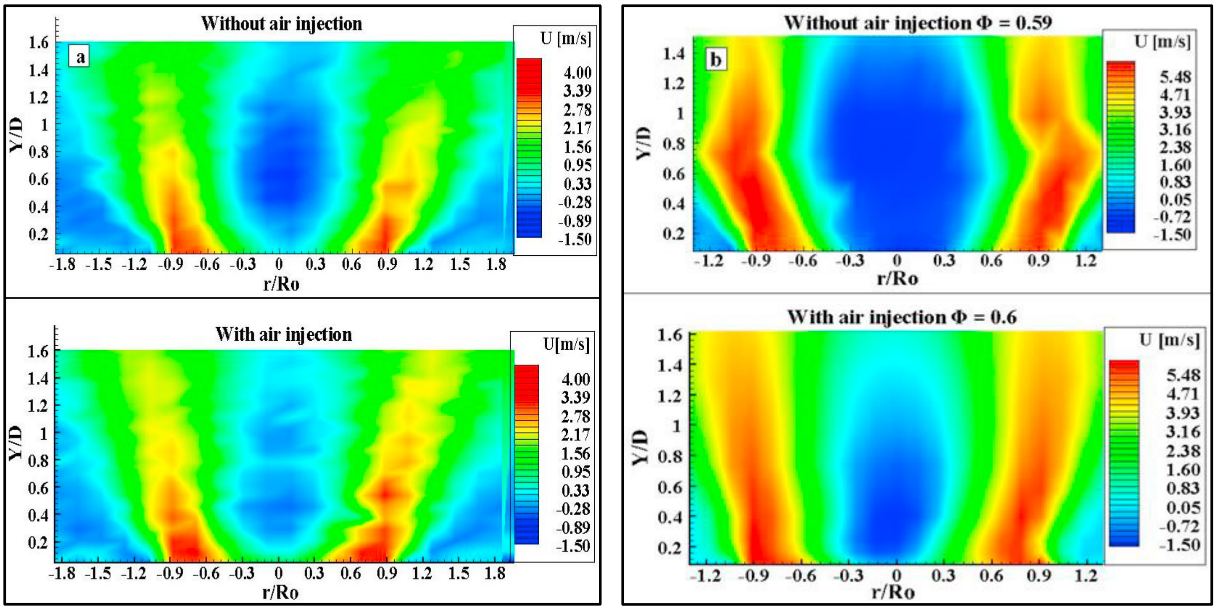

Fig. 4. LDA results, the effect of diffusive air injection on axial velocity downstream the burner mouth and the position of the CRZ. (a) Isothermal conditions, (b) Combustion conditions.

However, this effect is just for one-dimensional flow field. Three-dimensional verification is crucial in investigating this effect. Thus CFD analyses were obtained to consider the three-dimensional effects of axial air injection, Figure 5. It is clear that diffusive air injection reduces the defects in axial velocity values close to the burner mouth and pushes the CRZ.

3.2. *Micromesh surface for BLF resistance*

Although using central air injection can considerably tackle upstream flame propagation through the central core, especially CIVB, some drawbacks can arise, as the system could be more likely subjected to wall boundary layer

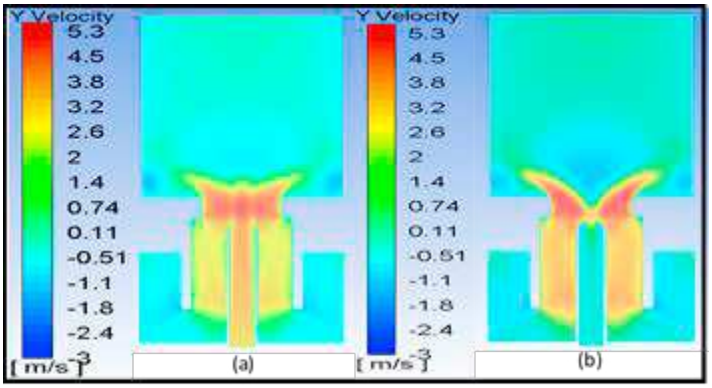

Fig. 5. CFD results, the effect of diffusive air injection on the position of the CRZ. (a) with air injection (b) without central air injection.

flashback (BLF), especially at higher tangential flowrates.The reason for this effect is that the central air injection produce moderate velocity gradients at the burner central axis by affecting the local axial velocity values at the tip and inside the CRZ. Consequently, this results in sharp velocity gradient near the wall, or in other words, the velocity gradient becomes less than its critical value, hence initiating BLF. However, by increasing the nozzle wall surface roughness by using the 150 μm grid as a liner, the sudden variation from high axial velocity values at the central axis of the nozzle to the low-velocity region near the wall are reduced. Consequently, lower gradients in the velocity values at the boundary layer region near to the nozzle wall are achieved as can be seen from figure 6.

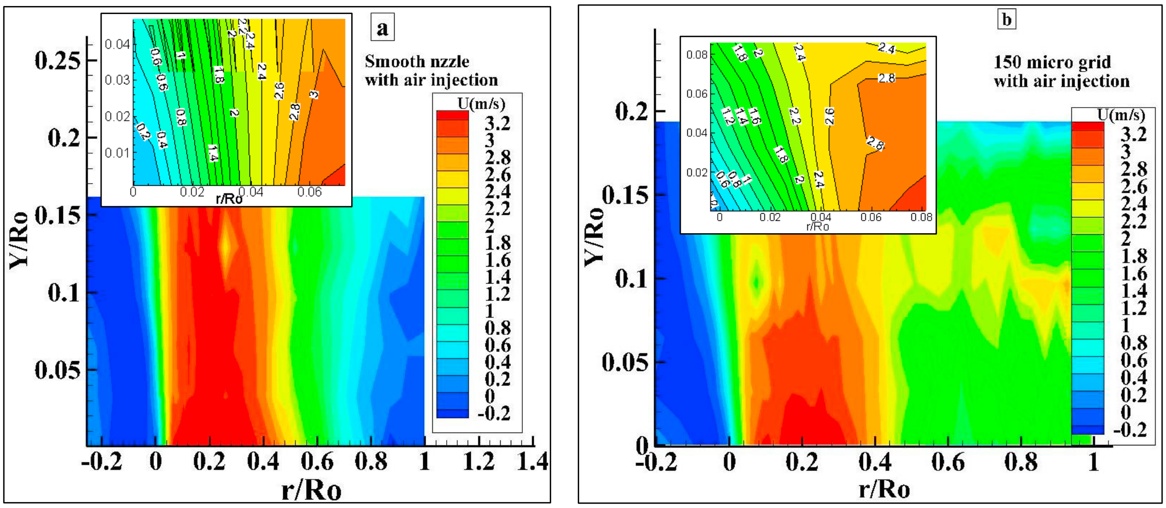

Fig. 6. LDA results, effect of nozzle wall surface geometry on velocity gradient close to the wall; a) smooth nozzle (no grid) with air injection; b) with 150 μm Grid and air injection.

3.3. *Mechanism of increasing flame flashback resistance for both CIVB and BLF*

Based on the previous results, it appears that the two flame flashback resistance mechanisms, i.e., air injection and microsurfaces, can work together to achieve highly flame flashback resistance for BLF and CIVB. Figure 7 illustrates flashback resistance scenarios when increasing equivalence ratio from stable operation (Φ_{stable}) to flashback conditions (Φ_{FB}). Figure 7-a represents stable operation where the flame is anchored downstream the nozzle. By increasing equivalence ratio the flame propagates upstream, figure 7-b. However the diffusive air injection prevent CIVB. Upon increasing equivalence ratio the diffusive air injection is still coherent enough to prevent upstream flame propagation, consequently enforcing the flame to propagate via outer shear layer, figure 7-c.

Further increase of equivalence ratio led the annular share layer to become totally in contact with the nozzle surface (i.e. the grid), with no flame flashback noticed, figure 7-d.

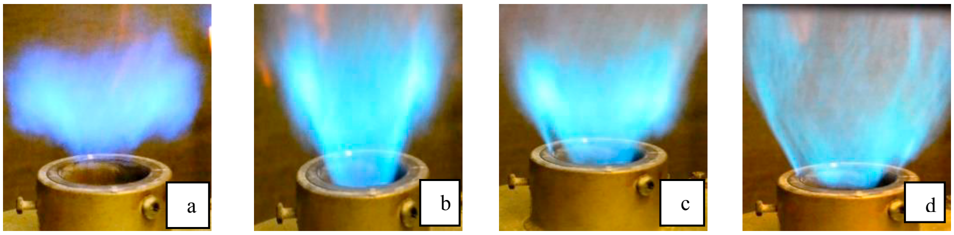

Fig. 7. Flashback resistance scenario for CIVB and BLF simultaneously.

4. Conclusions

1. Using central fuel injectors or diffusive air injection to improve flame flashback resistance against CIVB could lead to increase BLF, whereas such stylization techniques enforce the flame to propagation via wall boundary layer.
2. Increasing resistance against boundary layer flame flashback needs enhancement of the surface characteristics of the nozzle interior wall.
3. Using both air injection and micromesh configurations increase the stability limits considerably.
4. From an industrial point of view using such techniques is considered as a commercial solution to protect swirl combustors from CIVB and BLF at the same time.

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